Case Report

Combining robotic exoskeleton and body weight unweighing technology to promote walking activity in tetraplegia following SCI: A case study

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Context: To investigate the feasibility of combining the lower-limb exoskeleton and body weight unweighing technology for assisted walking in tetraplegia following spinal cord injury (SCI).

Findings: A 66-year-old participant with a complete SCI at the C7 level, graded on the American Spinal Injury Association Impairment Scale (AIS) as AIS A, participated in nine sessions of overground walking with the assistance from exoskeleton and body weight unweighing system. The participant could tolerate the intensity and ambulate with exoskeleton assistance for a short distance with acceptable and appropriate gait kinematics after training.

Conclusion: This report showed that using technology can assist non-ambulatory individuals following SCI to stand and ambulate with assistance which may promote general physical and psychological health if used in the long term.

Keywords: Lower-limb exoskeleton, BODY-weight support, Tetraplegia, Spinal cord injury, Rehabilitation

Introduction

The incidence of spinal cord injury (SCI) ranges from 10.4 and 83 per million people worldwide[1] and is approximately 17,000 new SCI cases per year in the United States.[2] SCI results in drastic changes that can be very debilitating to the affected individual. Without the ability to walk, individuals with SCI are forced into a sedentary lifestyle which is known to contribute to secondary medical problems such as obesity, osteoporosis/osteopenia, pulmonary and cardiovascular disease.[3] Recovery of locomotion function, therefore, is one of the primary goals in post-SCI rehabilitation. For persons with complete or/and cervical SCI, standing and walking activity could delay muscle atrophy, prevent contractures and osteoporosis while recovery of locomotion function may not be possible.[4]

Conventional post-SCI locomotion training usually requires two or more therapists manually guiding the patient's limbs during overground or treadmill walking.[5] Recent advancements in robot technology have led to the development of wearable robotic exoskeletons (WREs) that can deliver less labor-intensive, more consistent gait kinematics during overground locomotion.[6,7] Individuals without sufficient upper limb function (*i.e.* tetraplegia) usually are not being considered for the use of WREs, although one study has shown that they could ambulate with WRE using bilateral platform rolling walker.[8]

This case report is to demonstrate the feasibility of combining the overhead track-following body weight support (BWS) system with WRE to assist overground walking in an individual with tetraplegia following SCI. Specifically, we intend to explore whether a participant

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with a cervical motor/sensory complete spinal cord injury could tolerate the training set-ups and intensity.

Methods

Participants

A 66-year-old Caucasian male (height 1.77 m, weight 90.72 kg) with complete (C7 AIS A) non-ambulatory SCI participated in this case study after providing informed consent as approved by the Institutional Review Board (IRB) at the University. He incurred a traumatic SCI at C7 level 83 months ago and had no palpable contractions and no increase in muscle spasticity in either of his lower limbs (Modified Ashworth Scale: 0). The participant possessed sufficient passive range of motion in lower limb joints required to use the exoskeleton, intact skin on all surfaces in contact with exoskeleton and load-bearing system. He was also cognitively intact and able to follow directions and demonstrate learning capability.

Training and assessment protocol

The training involved a combination of a BWS system (Vector Gait & Safety System®, Bioness Inc., Valencia, CA, United States) and a WRE (Ekso™ (version 1.1), Ekso Bionics®, CA, United States). Vector Gait & Safety System® is a dynamic BWS system that designed to provide a constant weight unloading during overground gait rehabilitation and balance training. The purpose of BWS was to ensure the safety of the participant and provide additional physical assistance. Ekso™ (version 1.1) is a wearable, battery-operated bionic WRE that enables patients with lower-extremity weakness or paralysis to stand and walk on level surfaces. It is equipped with powered actuators at hip and knee joints to deliver torques during locomotion and therefore is designed to assist an efficient reciprocal gait pattern during post-injury rehabilitation. At beginning, the participant underwent a whole-body bone mineral density scan and orthopedic hypotension assessment using a tilting table. We also measured spasticity on the upper and lower limbs using the Modified Ashworth Scale. The participant then participated in nine 1-hour training sessions (five sessions in the first week, two sessions in the second week, and two sessions in the third week). A physical therapist (trainer) and one research staff assisted and performed training. Each session started with the trainer assisting the participant in donning the WRE and subsequently attached to the BWS system. The complete experiment setup is shown in Fig. 1a.

During the training, the participant was instructed to initiate and perform mediolateral weight shifting with his arms. The participant did not use any assistive device during training. Initially, each step was triggered via a wired controller by the research staff (First Step mode). The trainer assisted the participant (with minimum to moderate physical assistance) to shift the weight from back to ensure foot clearance and smooth swing. The training mode then progressed to Pro Step mode. The participant was encouraged to perform the task as much as possible (along with a 38 m U-shaped path, Fig. 1b). The training parameters including step length, step height, swing time, knee flexion angle, hip flexion angle, forward weight shift and lateral weight shift were adjusted as needed to execute steps with appropriate gait kinematics. The amount of BWS was set between 10 to 20% of total body weight based on clinical experience. The participant was asked about his perceived exertion periodically using the Borg Scale of Perceived Exertion.

After training, the lower-limb kinematics were collected (using Opotrak Certus® system, Northern Digital Inc., Ontario, Canada) during the exoskeleton and weight support system-assisted walking to evaluate the participant's gait kinematics. The participant also completed a questionnaire to evaluate the user's experience and the user-perceived improvements of using the WRE for walking on health, as a therapeutic tool, mobility and independence and psychosocial factors. Besides, there are device-related questions to evaluate the user's experience regarding transfer, ease of use and WRE's speed.

Results

The participant was able to stand upright and successfully finished nine walk training session with the assistance from the WRE and body weight suspension system. Figure 2a demonstrates the gait cycle (defined as epoch between two consecutive ipsilateral heel strikes) angular position of all lower limb joints in the sagittal plane in the post-assessment session.

The progression of the up time and walk time, total steps and walking speed during training is presented in Fig. 2b. The up time (standing time with support of WRE and BWS system), walk time, total steps (walk distance) and steps / second (step speed) with regard to training session index are visualized and their best polynomial fit curves (red line) based on minimum root mean square error criterion is overlaid. As shown, all four measurements increased as a linear function of the training session index. Compared to the first session, the participant reached 8.5 times of walk distance and almost doubled his walk speed by the end of the training.

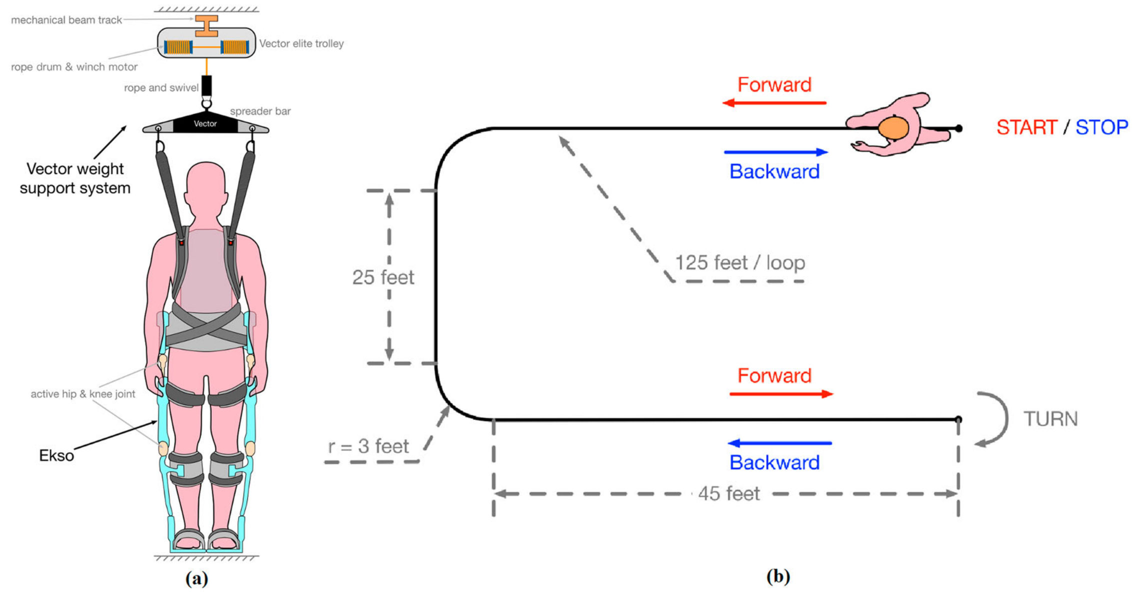

Figure 1 (a) Experiment setup. (b) Gait training path and dimension.

According to the user feedback, the participant's perception was that the WRE could help him improve his bone density, circulation, and skin integrity. However, he did not expect an improvement in spasticity, pain, or excretory functions. Regarding strength and mobility, the participant expected this training to improve strength, but feels that it is unlikely that independent ambulation can be achieved.

Despite unclear therapeutic benefits, the participant felt that "the experience of a normal stride was marvelous." This alone was helpful in boosting the morale of the participant to keep training. The participant noted an expected improvement in social interaction, self-esteem, quality of life, and psychological health through the future use of the WRE.

Discussion

This case report demonstrated the feasibility of combining WRE and dynamic BWS system to assist a non-ambulatory tetraplegia individual following SCI in walking overground. As the participant is non-ambulatory, the purpose of the use of the technology is to provide an alternative opportunity for the tetraplegic individuals to maintain an upright posture, induce loading to lower extremity and exercise. The increases in up time, walk time and distance during exoskeleton assisted walking indicates that the participant could learn to interact with the devices and trainer to perform the task. The participant was able to tolerate the training procedure and complete the training. With dynamic BWS system which provides partial body off-loading

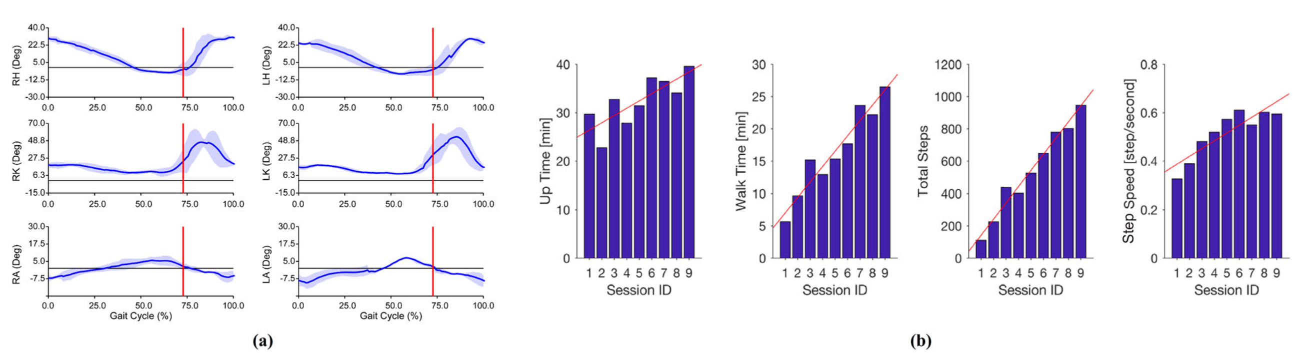

Figure 2 (a) Joints' angular position during gait cycle (RH, right hip; RK, right knee; RA, right ankle; LH, left hip: LK, left knee; LA, left ankle. Blue solid line = average joint angles; blue shade = joint angle standard deviation range; Red vertical line = average toe off time). (b) The progression of the up and walk time, total steps and step speed during training.

and fall prevention, exoskeleton assisted walking in individuals with tetraplegia is feasible and safe. The perceived benefits of technology-assisted activity including improvement in social interaction, self-esteem, and psychological health may lead to improved quality of life.

Regarding kinematics, despite the significant longer stance phase (approximately 70%) than the normative gait pattern (60% stance phase),[9] the participant's lower limb joint angular position during exoskeleton assisted walking was within acceptable range and consistent, although the range was small which could be a result of slow walking speed in exoskeleton.[10]

With more settings adopting robotic technologies, post-SCI individuals could start training with the combination of WRE and dynamic BWS system as early as possible and receive the training in every phase of the continuum of rehabilitation after SCI. For individuals that regaining ambulation function is not the top priority during their recovery, this training may provide therapeutic benefits including preventing/delaying deterioration of musculoskeletal system and promoting psychosocial health. Moreover, greater assistance is needed to run rehabilitation therapy safely for tetraplegic participants. The combination of the WRE and BWS system ensures both participants and trainer a more extended tolerance for this labor-intensive training.

Conclusion

In this study, we have demonstrated that a participant with tetraplegia could walk overground in a WRE combined with a dynamic BWS system. The results suggest that the combination of the devices allows the participant to take steps that would otherwise be impossible to achieve with a sole physical therapist. Although the long-term therapeutic benefits remain unclear, this combination provides an opportunity for the trainer to develop an alternative novel gait rehabilitation therapy for persons with tetraplegia.

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